

Tomographic Sounding of Protoplanetary and Transitional Disks: Using Inner Disk Variability at Near to Mid-IR Wavelengths to Probe Conditions in the Outer Disk

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Synoptic Studies of Star Forming Regions - Spitzer

- Have demonstrated that mid-IR variability is ubiquitous among young stars (Rebull 2011; Kóspál et al. 2012)
- Ranges from rotational modulation (star spots) and flaring
- Accretion variability
- Larger scale outbursts such as EX Ori variation (Ábrahám, et al. 2009; Juhász et al. 2012)
- Warped disks (Flaherty et al. 2013)

Strengths of Spitzer Studies

- Photometrically stable and calibrated
- Can acquire data for large star-forming regions with minimal number of pointings – hundreds of objects monitored
- Complements similar studies in the X-ray

Limitations of Spitzer-Based Studies

- Limited to a few year baseline
- Better at short-term (hours to day to day) timescales than sampling changes on months to years due to scheduling constraints
- Typically require data at other wavelengths to go beyond “It varies, now what?”, particularly for warm mission data.

Long-Duration Synoptic Studies

- Alternate approach is to follow a small number of objects and to coordinate with imaging and interferometric studies. Begun in mid-1990s, but some data from late 70s onward
- Initial targets are objects which could be studied from space using IUE, ISO, HST augmented with ground-based data (IRTF/SpeX, REM, BASS)
- Large and growing overlap with targets for high-contrast imaging studies
- More recent expansion into interferometric targets

Protoplanetary Disks

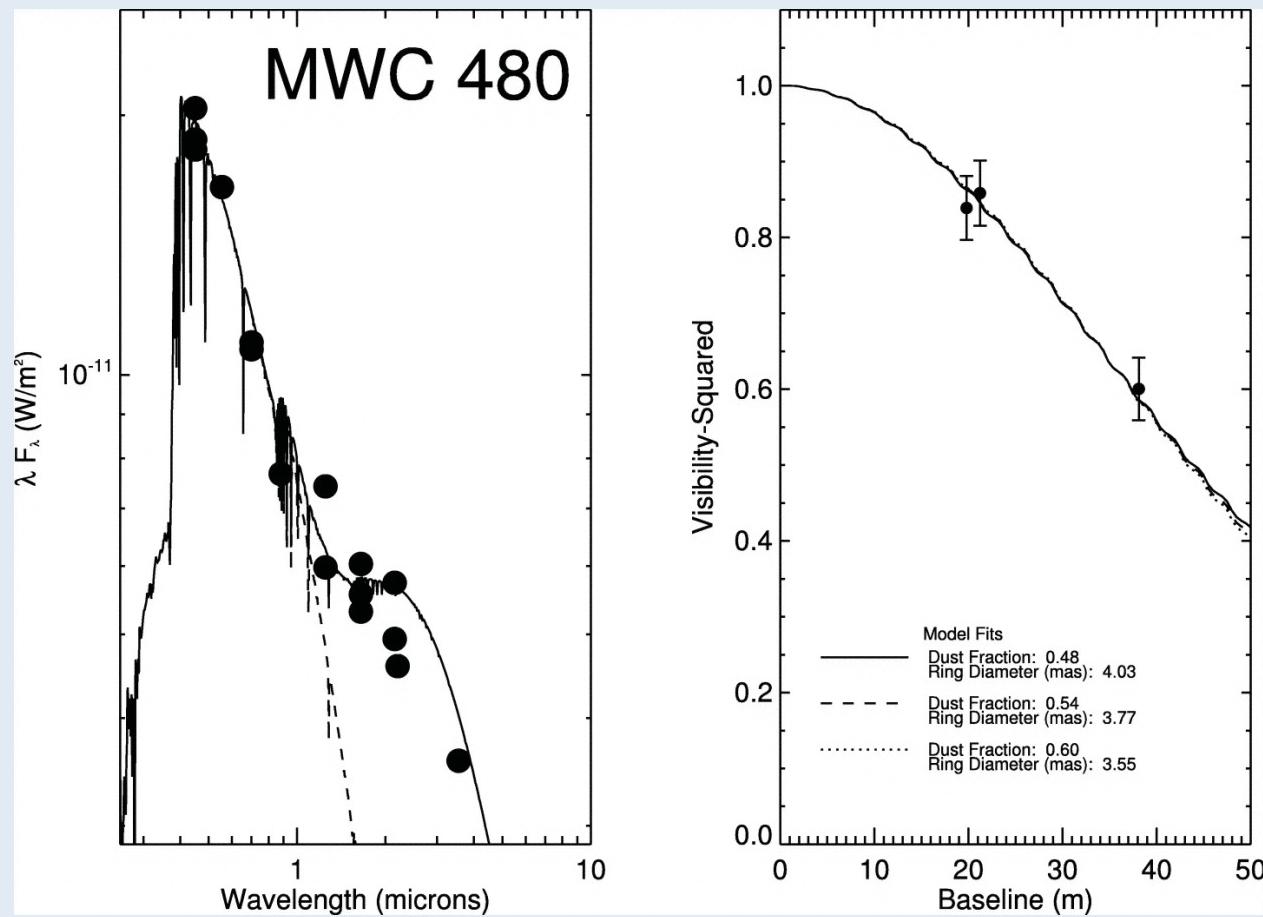
- HD 163296 – A1Ve, d=122 pc, E(B-V)=0.015, ALMA early release target
 - imaging of sub-mm continuum in disk and gas (de Gregorio-Monsalvo et al. 2013)
 - Disk vertical structure (Rosenfeld et al. 2013)
 - Molecular wind (Klaasen et al. 2013)
 - Snow lines resolved for various gas-phase species (Matthews et al. 2013)
- MWC 480 most massive of Herbig Ae disks (Mannings, Koerner, & Sargent 1998)
 - rich gas spectrum (Piétu et al. 2007, Guilloteau et al. 2012, 2013; Chapillon et al. 2012)

Predictions from SED Shape

- Herbig Ae stars have two distinct IR SED morphologies: power law only from 1-200 μm , or power law + blackbody component (Meeus et al. 2001)
- Power law only (Meeus group II) have been interpreted as disks where grain growth and settling have occurred (Dullemond & Dominik 2004a,b), while group I have been interpreted as flared disks.
- Can test via high-contrast imaging, or multi-line sub-mm interferometry and with synoptic data.

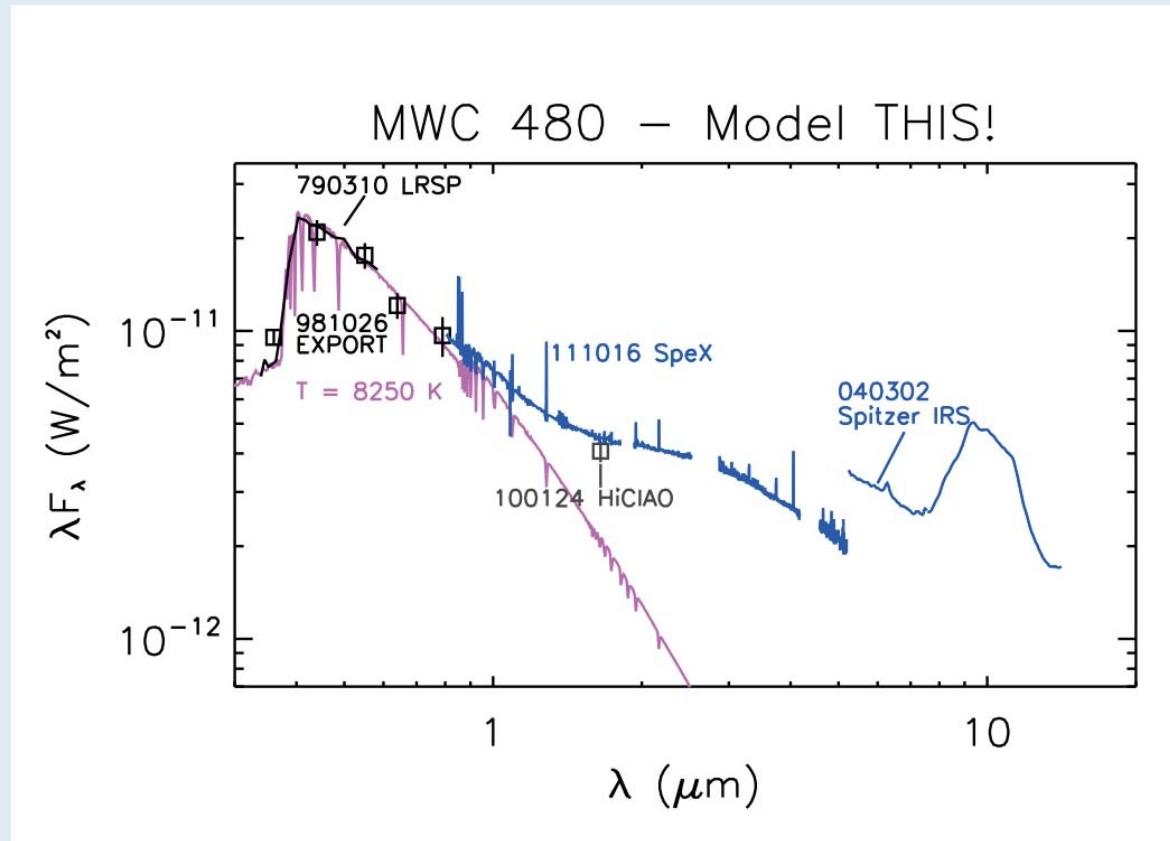
MWC 480 – Meeus group II

- History of NIR SED variability (Sitko et al. 2008)
- History of disk non-detection in scattered light (Grady et al. 2010)
- Finally saw the disk in scattered light with HiCIAO at H
 - Initial thought was that the instrument was performing much better than HST....



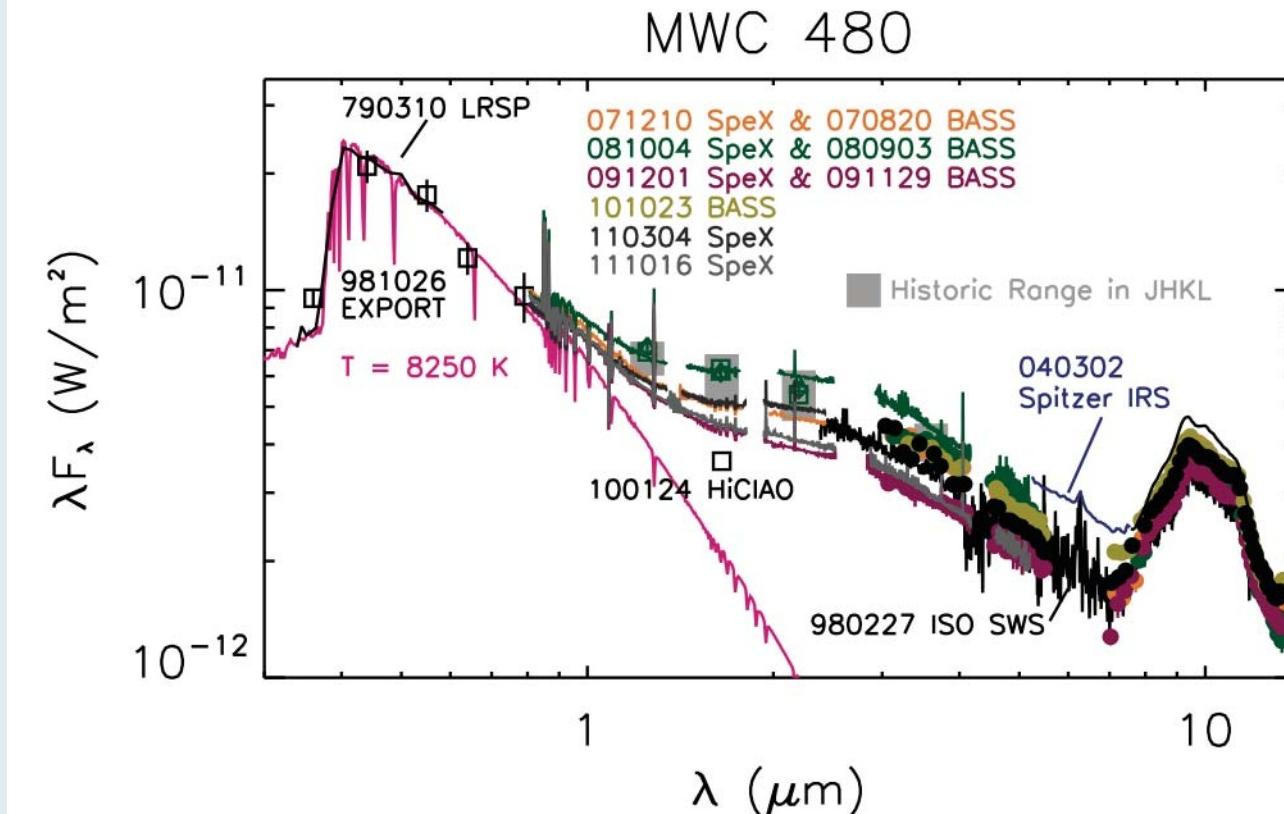
MWC 480: NIR photometry and model fitting :
At left is the stellar photosphere (dashed line) and photosphere + disk (solid line). Filled circles are data from the literature.

If you were to try to model the SED using data obtained at different epochs, you might be forced to try to fit this:



LESSON: SED DATA MUST BE OBTAINED USING CONTEMPORANEOUS OBSERVATIONS, NOT UNCOORDINATED OBSERVING SESSIONS. THIS REQUIRES COORDINATING OBSERVING SCHEDULES ACROSS MANY FACILITIES.

More complete View: NIR SEDs

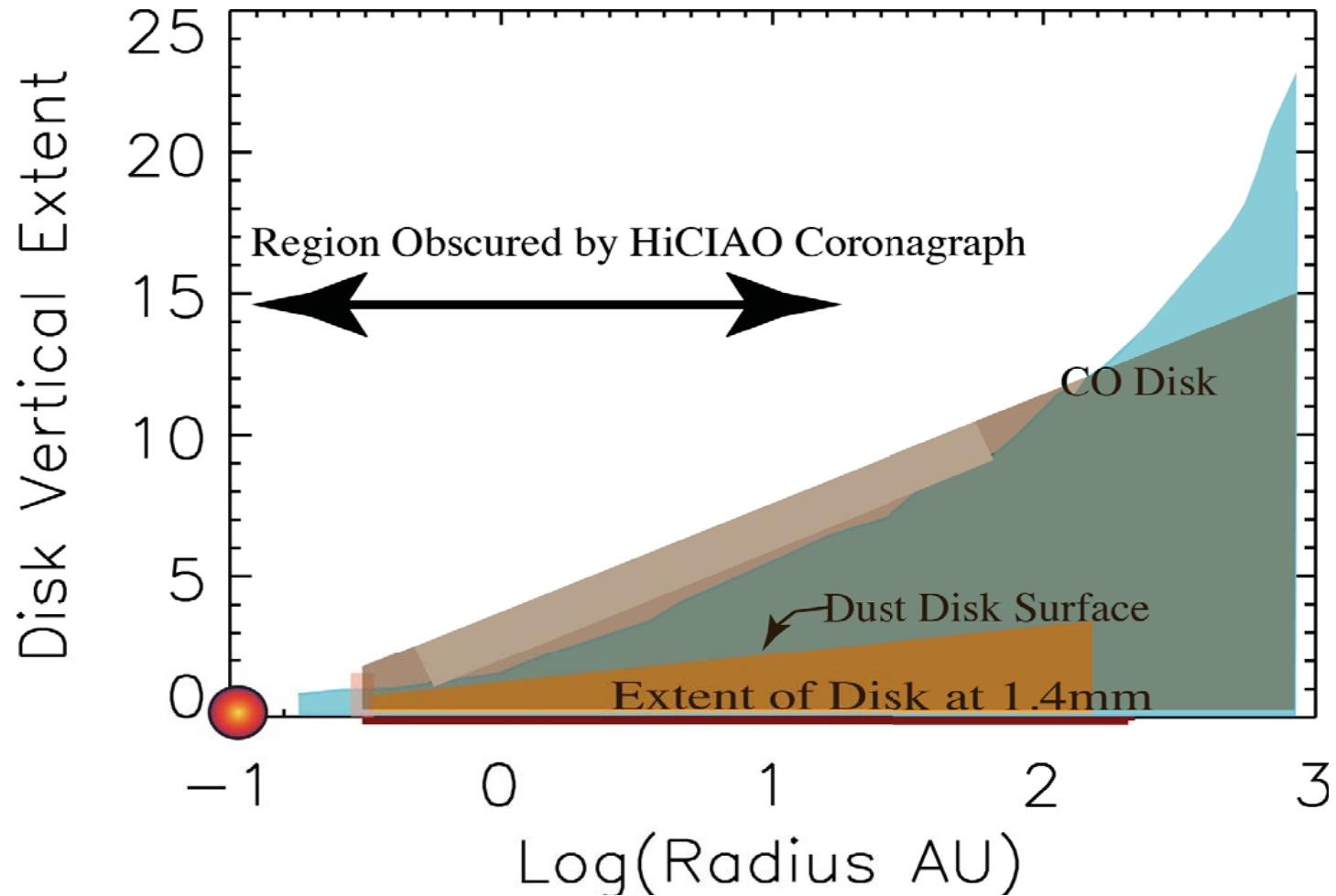


The near-IR flux of MWC 480 can change dramatically over a few months. The changes are intrinsic to the source, not observational uncertainties.

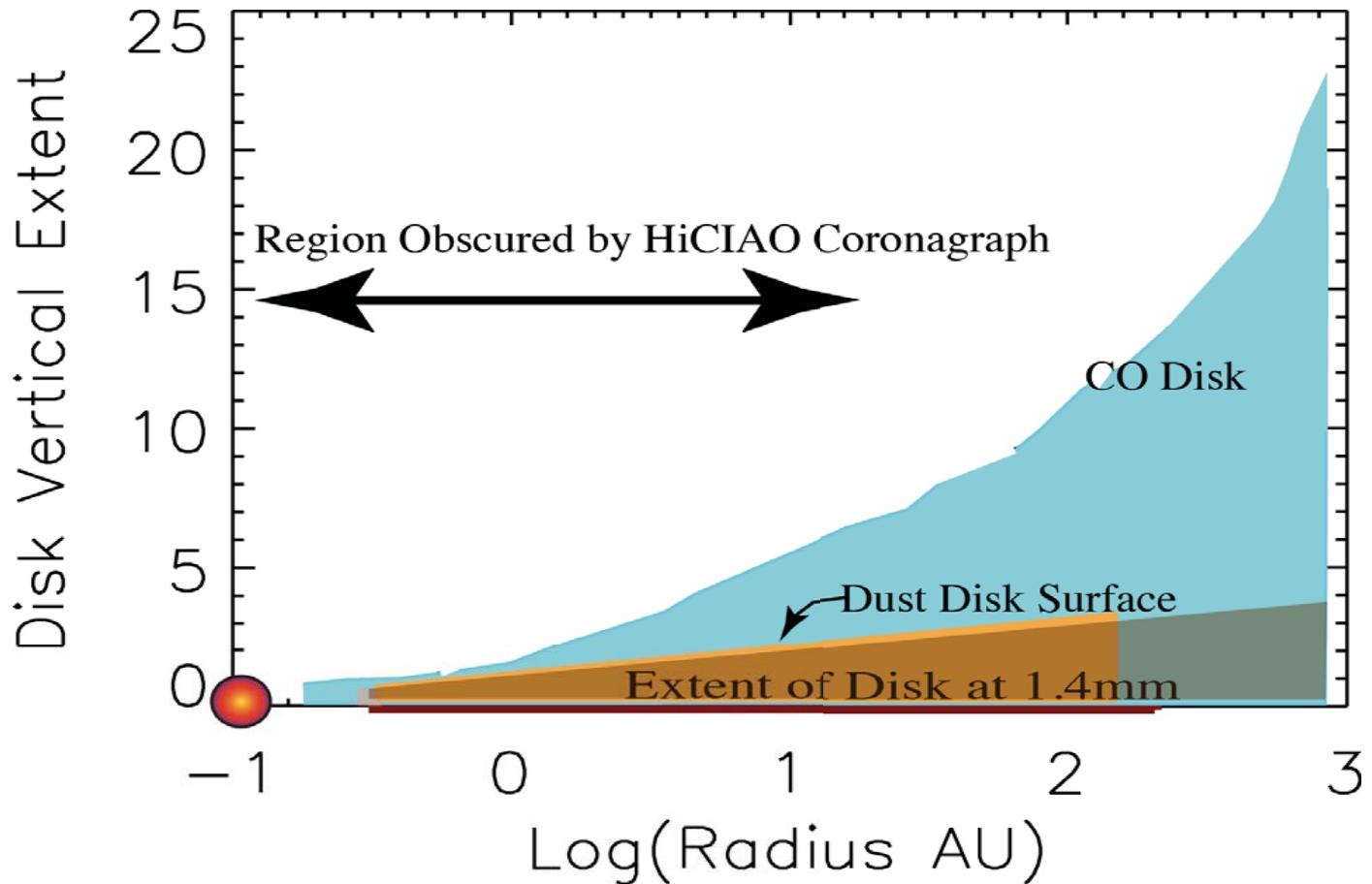
Anti-Correlation between Disk Detection and 3 μ m excess

- Disk undetected (04 NICMOS) at high IRE
- Disk marginally detected at medium IRE (98 ISO data, Grady et al. 2010)
- Disk firmly detected at historic low IRE (Kusakabe et al. 2012)
- 3 μ m continuum and 9.7 μ m silicate feature come from \sim 1 AU in the disk, near the dust sublimation radius
- Trend suggests variable shadowing of the outer disk

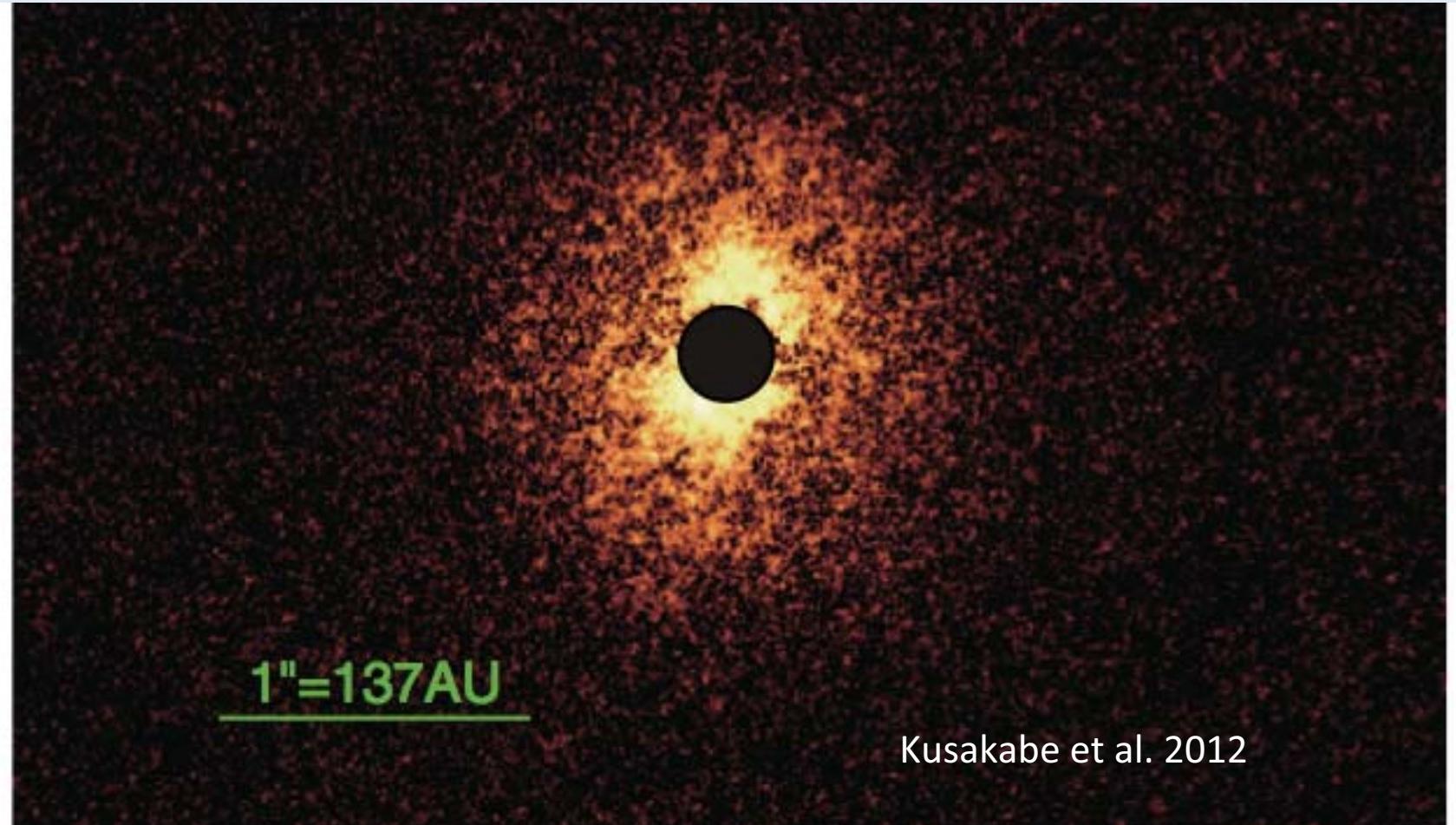
Using the IRE to estimate disk scale height at sublimation radius



Using the IRE to estimate disk scale height at sublimation radius



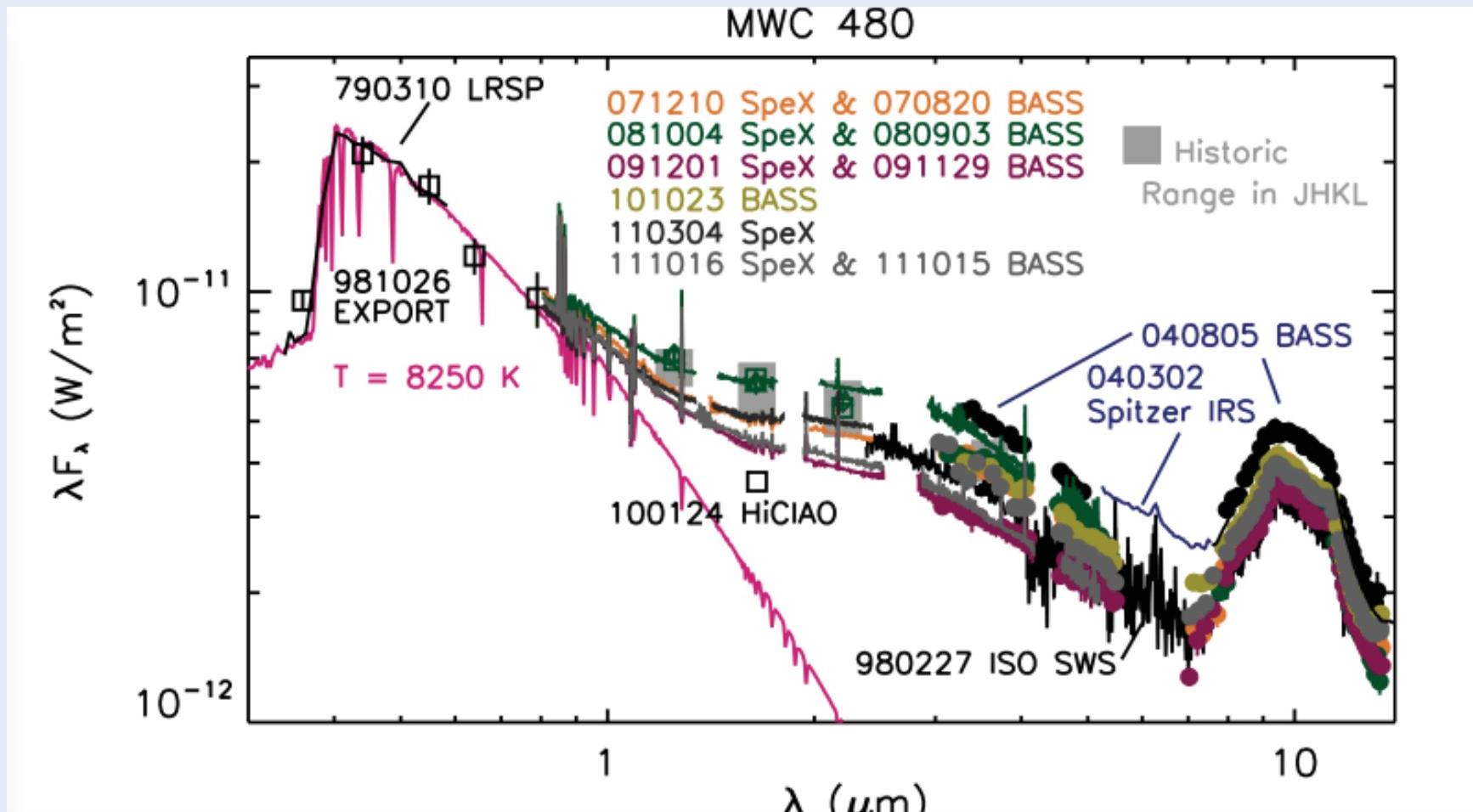
MWC 480- H-band polarized intensity



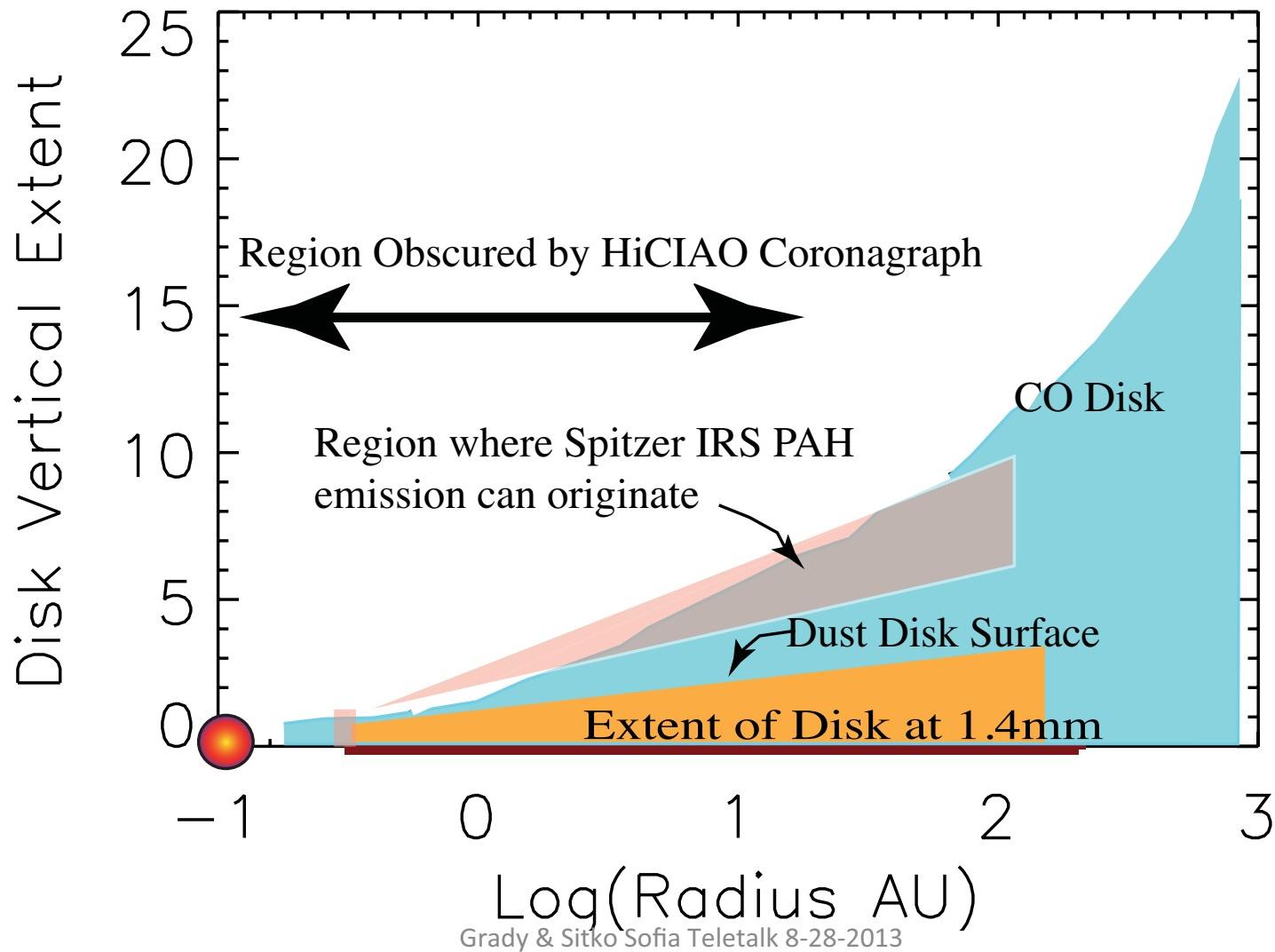
Dust Disk Structure

- Dust disk surface for MWC 480 lies between $1.6^\circ < \theta < 2.2^\circ$, based on the HiCIAO and ISO data
- $H \sim 3$ AU at 100 AU - Small scale height consistent with dust grain growth and settling
- Factor of 3 lower in scale height than gas disk – may be close to violating model assumptions that gas and dust are well-mixed.

PAH Emission at maximum IRE



Can also probe where species that are photo-excited are located in spectra

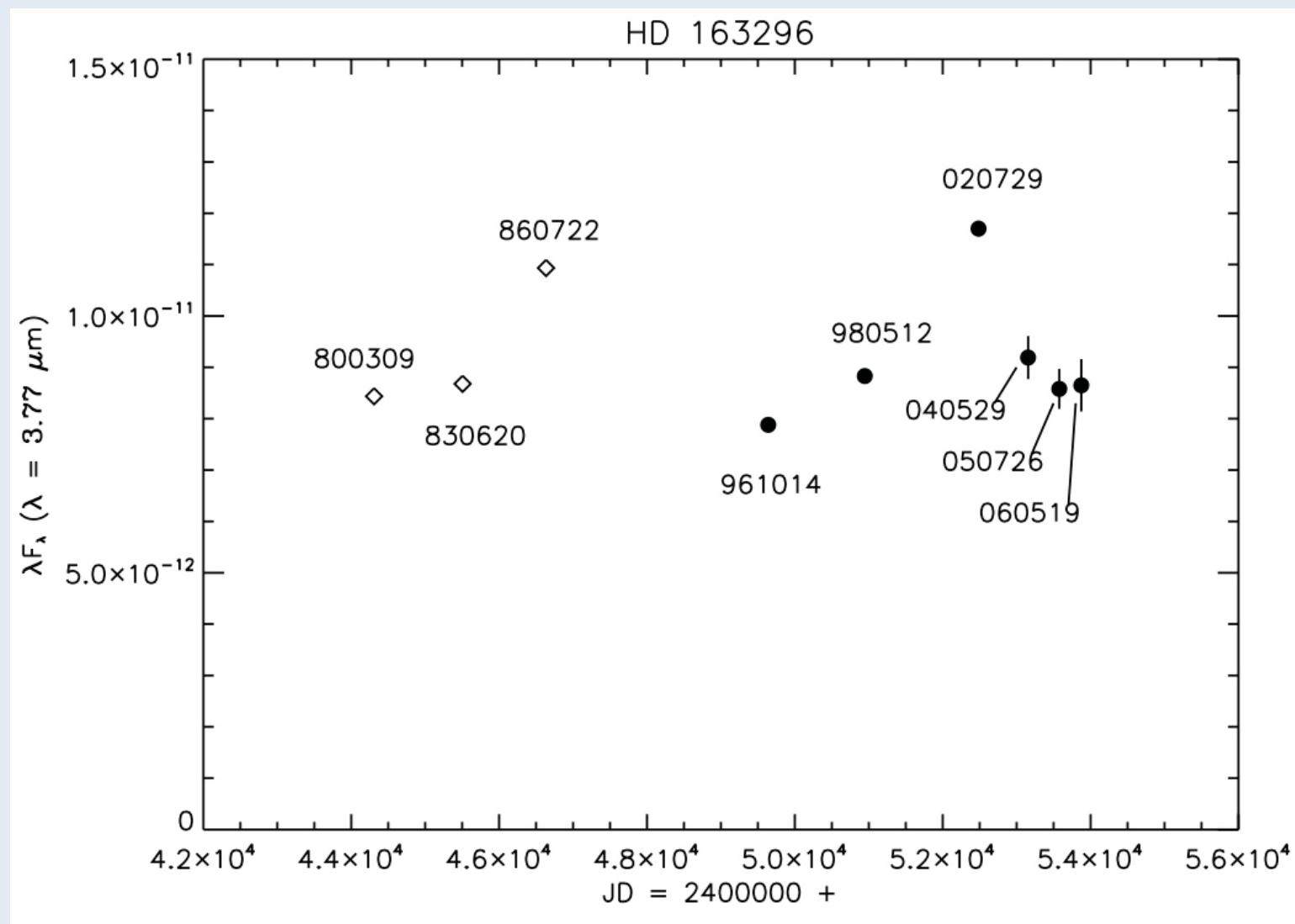


Locating the PAHs

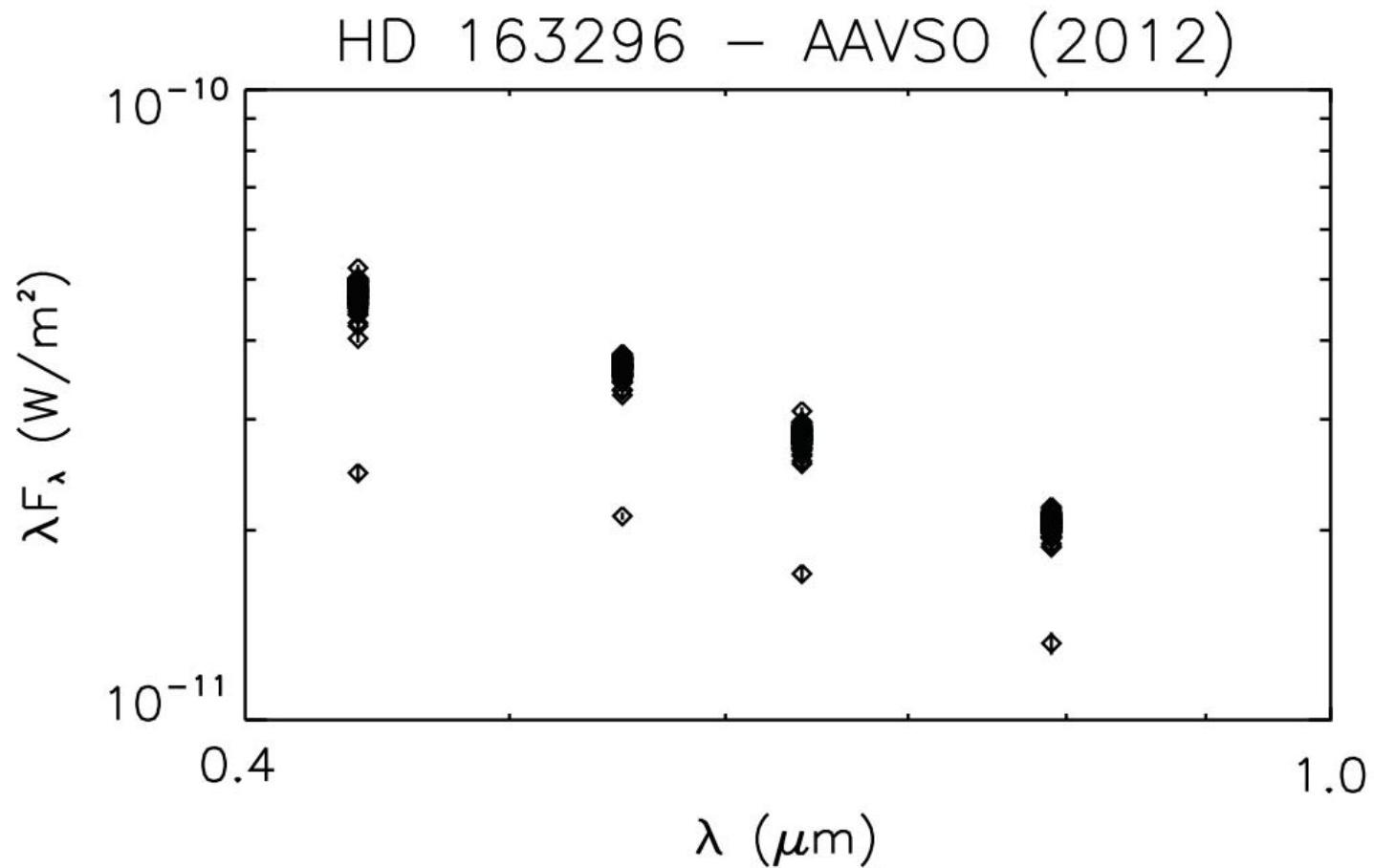
- If restricted to near the dust sublimation radius, should be always visible (given sufficient S/N), but relatively faint
- If located over more of the disk surface, should see enhanced line/continuum when disk is faint and more of the disk atmosphere is lit by the star as well as variable net flux.
- Might expect different patterns of variability depending on the size/mass of the carrier molecule.
- Distinguishing between these options is goal of our cycle 1 SOFIA study of MWC 480 and HD 163296.

HD 163296

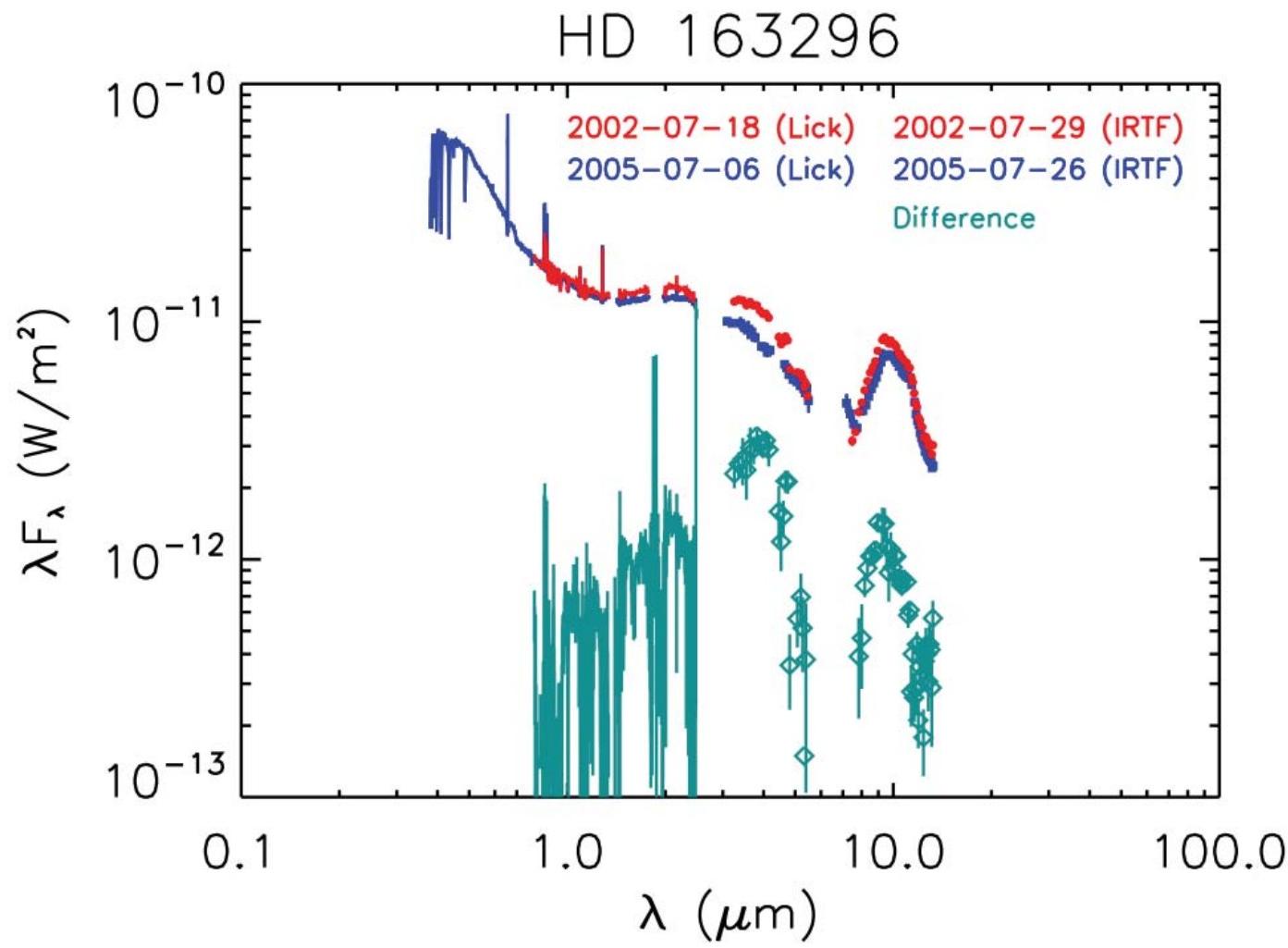
- Similar SED variability; imaging detections initially (Grady et al. 2000; Fukagawa et al. 2010; Wisniewski et al. 2008)
- More recent HiCIAO data at maximum IRE have been scattered light non-detections.
- Potential 15.3 year period in HH knot ejections (Ellerbroek et al. 2013, in prep.) IR max. state at epoch of 2002 knot ejection.
- Full disk is not shadowed all the time, and illumination duty cycle may be higher than for MWC 480.



Long-term changes in the brightness of the near-IR “hump”

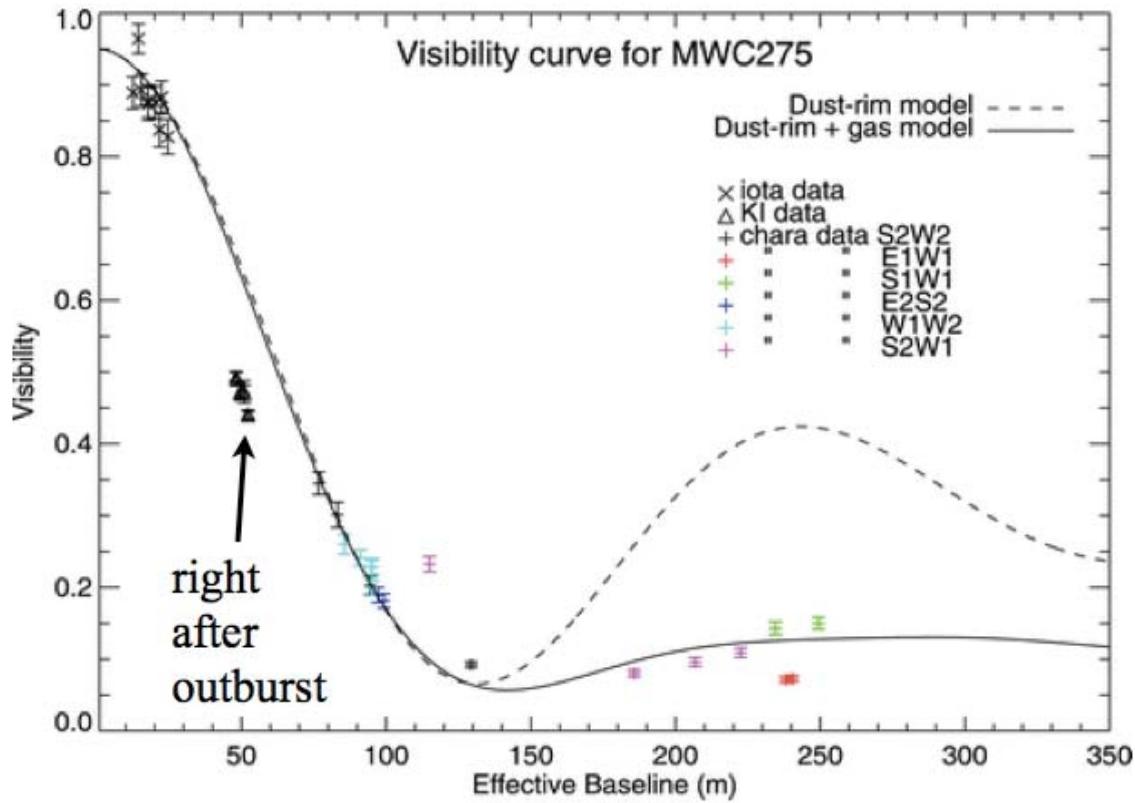


The BVRI SED of HD 163296 in 2012. AAVSO. It is also undergoing UX Ori-like occultation events.

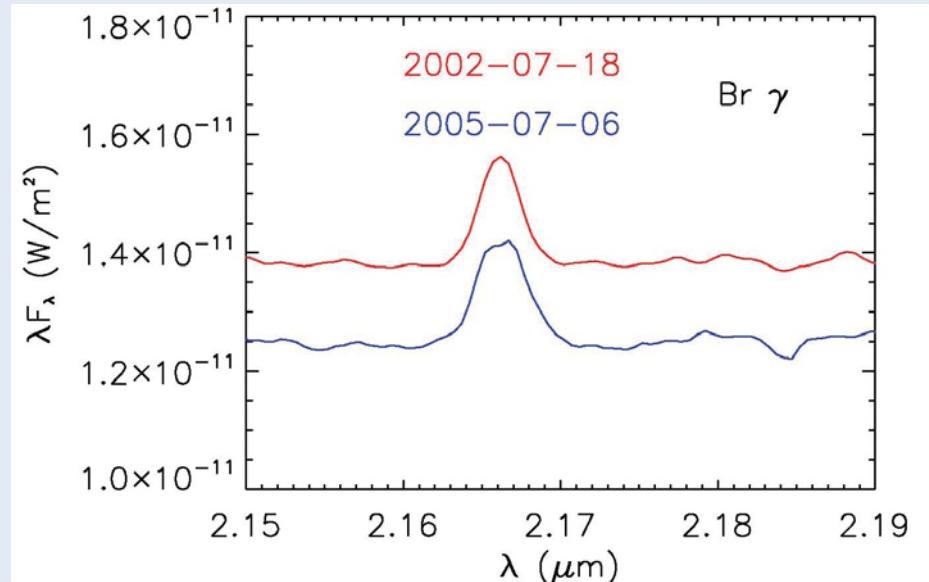
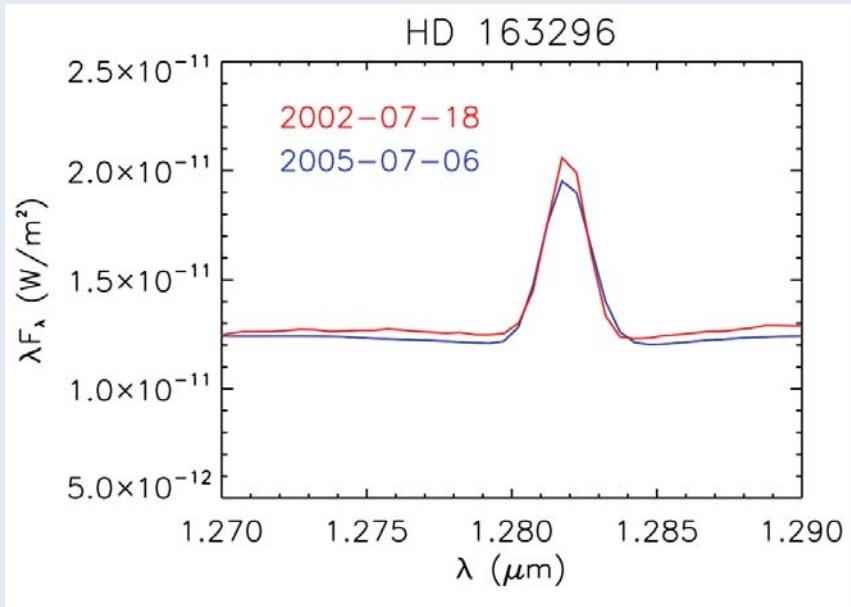


An example of the variable SED of HD 163296 = MWC 275. The lower curve is the difference between the fluxes of the two epochs. From Sitko et al. 2008.

HD 163296 = MWC 275



In 2003, not long after the 2002 “outburst”, the Keck Interferometer detected a change in the fringe visibility consistent with a 20% change in the diameter of the “cleared” inner opening inside the dust disk wall.
Adapted from Tannirkulam et al. 2008.

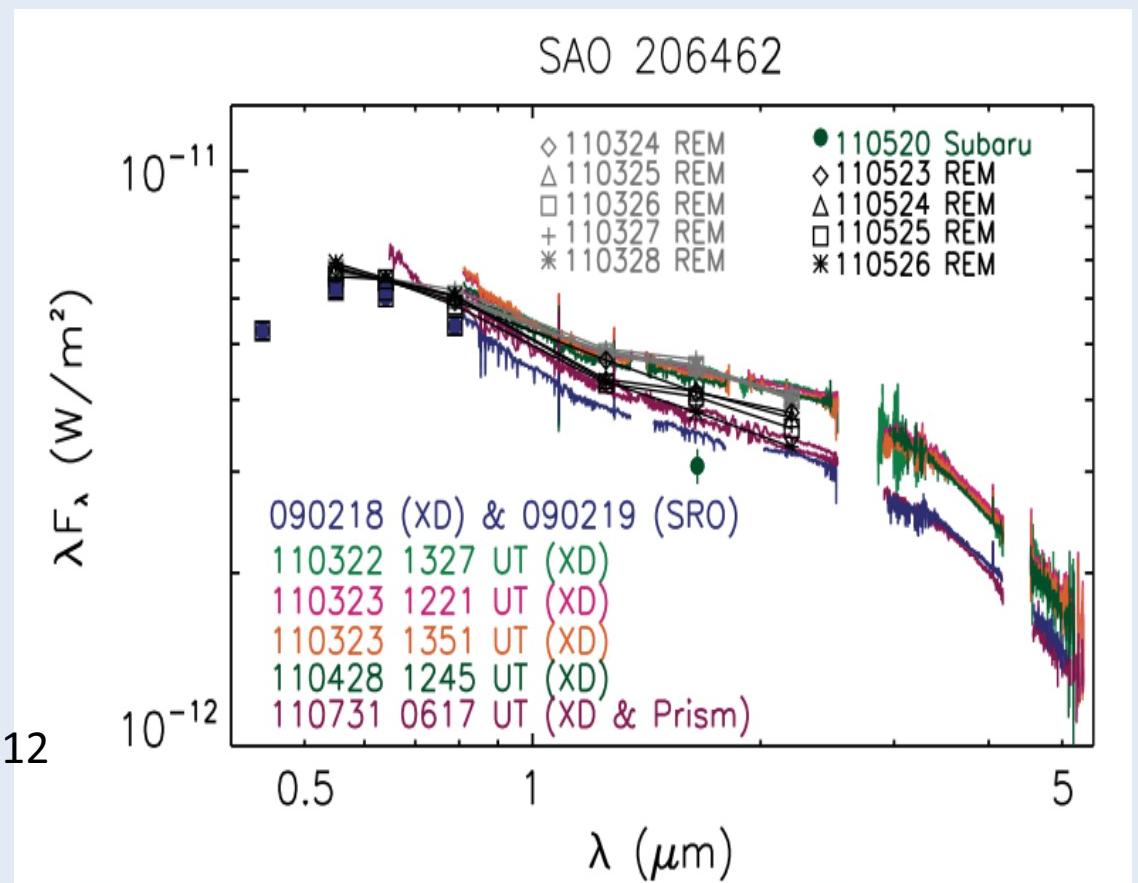
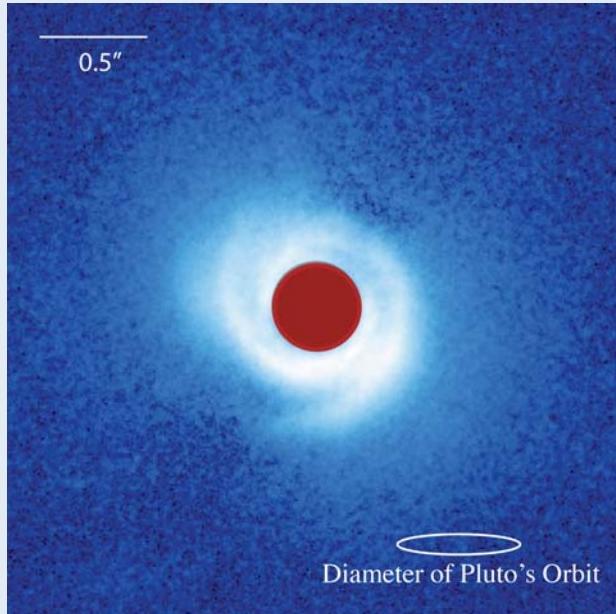


The interferometry indicated that the SED change was due to some change in the STRUCTURE of the inner disk region (this also seemed to coincide with a jet outburst – Ellerbroek et al., in preparation). The stability of the “usual” measures of disk accretion showed that this change was NOT the result of added heating from accretion onto the star! It has another cause.....

Shadowing in (Pre-)Transitional Disks

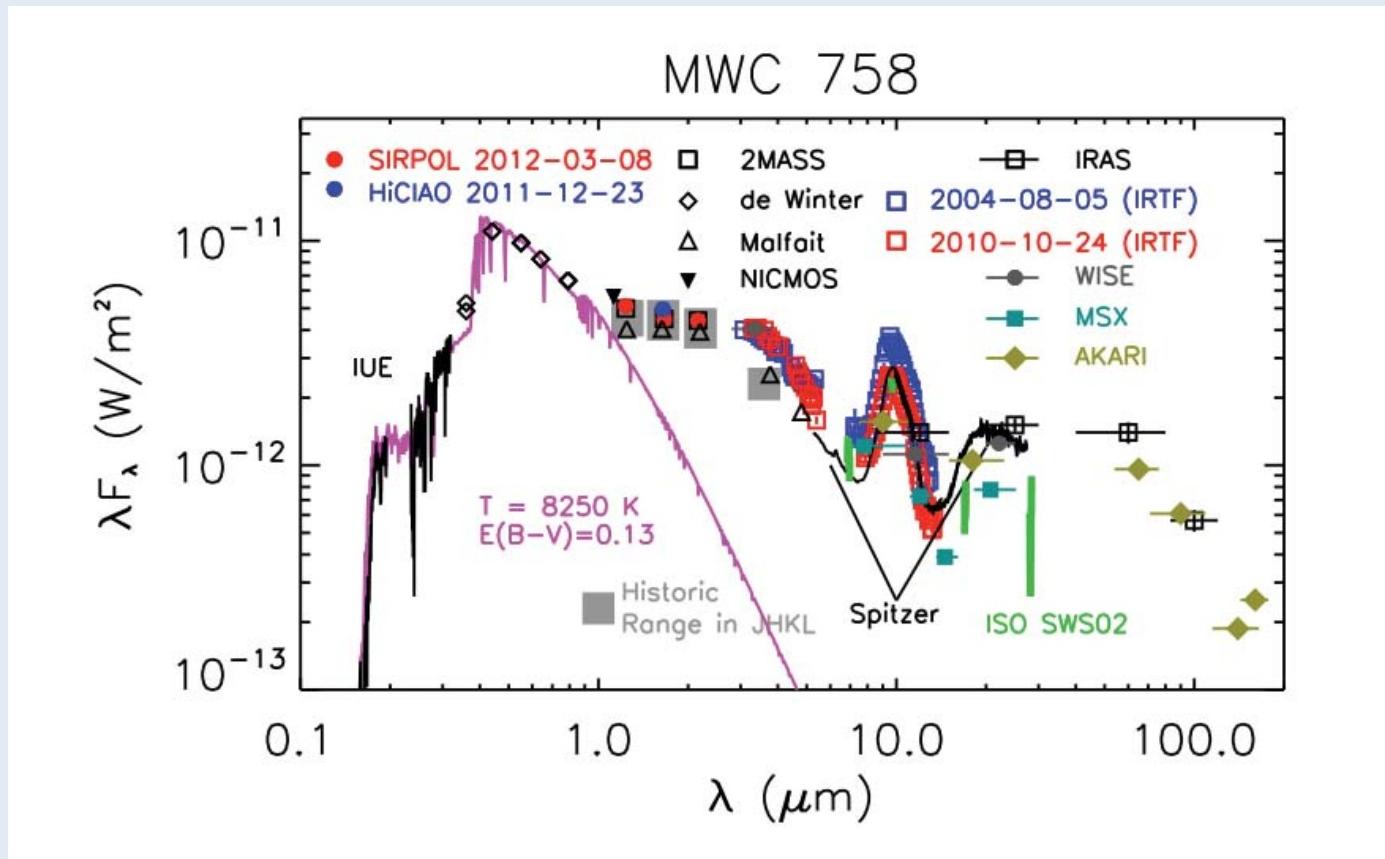
- Inner disk variability not limited to protoplanetary disks, but also in pre-transitional disks
- Now documented for
 - SAO 206462,
 - MWC 758, and
 - HD 169142

SAO 206462



Inner disk variable in temperature and IRE – in extended state can be fit with 20° inclination, 10° more than the outer disk – interferometry also suggests inner disk may not be coplanar with outer disk (Benisty, priv. comm.) Variability night-to-night but distinct on 6 week timescales.

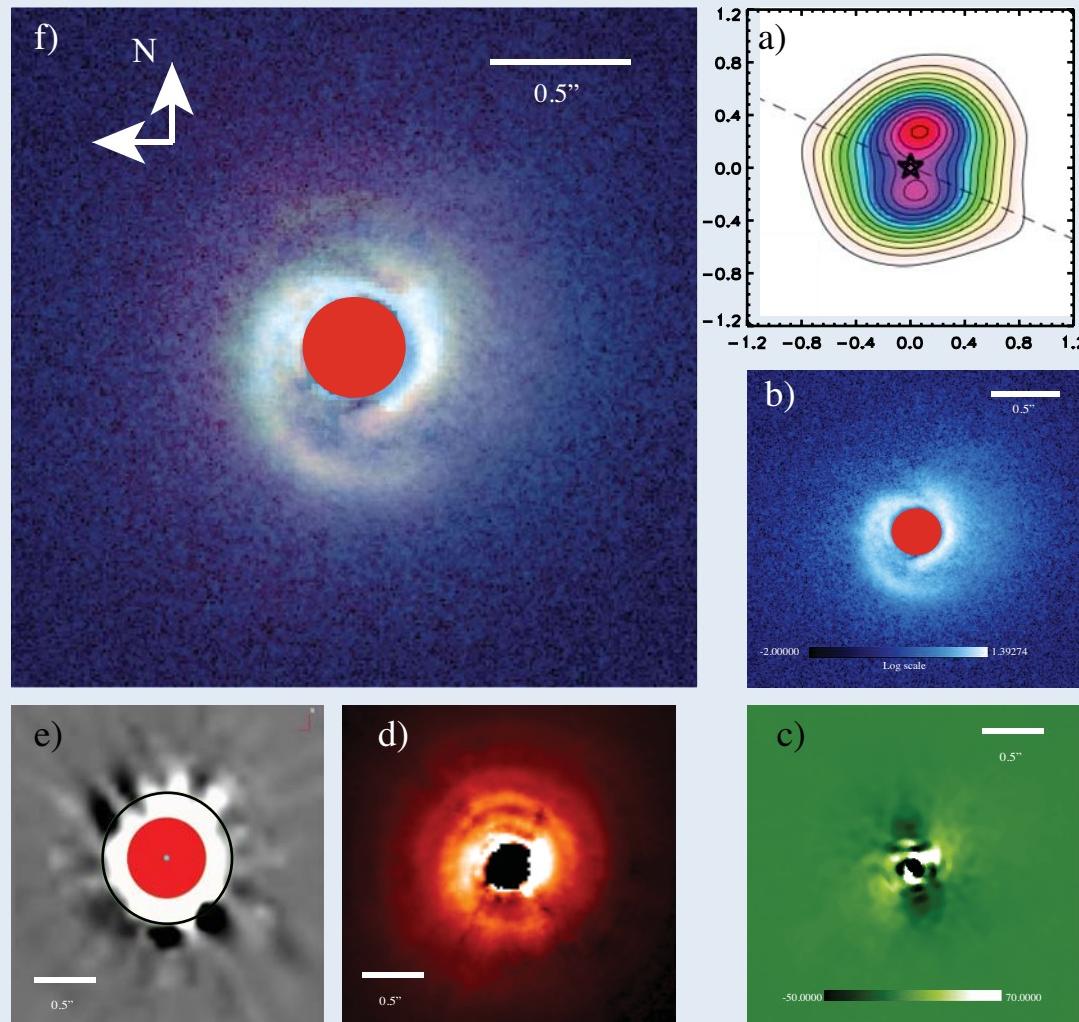
MWC 758



Multi-epoch SED clearly shows mid-IR dip characteristic of transitional disks – some indication that the dip was deeper and/or extended to longer wavelength at the epoch of the MSX observations. Interferometry suggests inner disk may not be coplanar with outer disk (Isella et al. 2008; 2010).

MWC 758 – in scattered light

Grady et al. 2013



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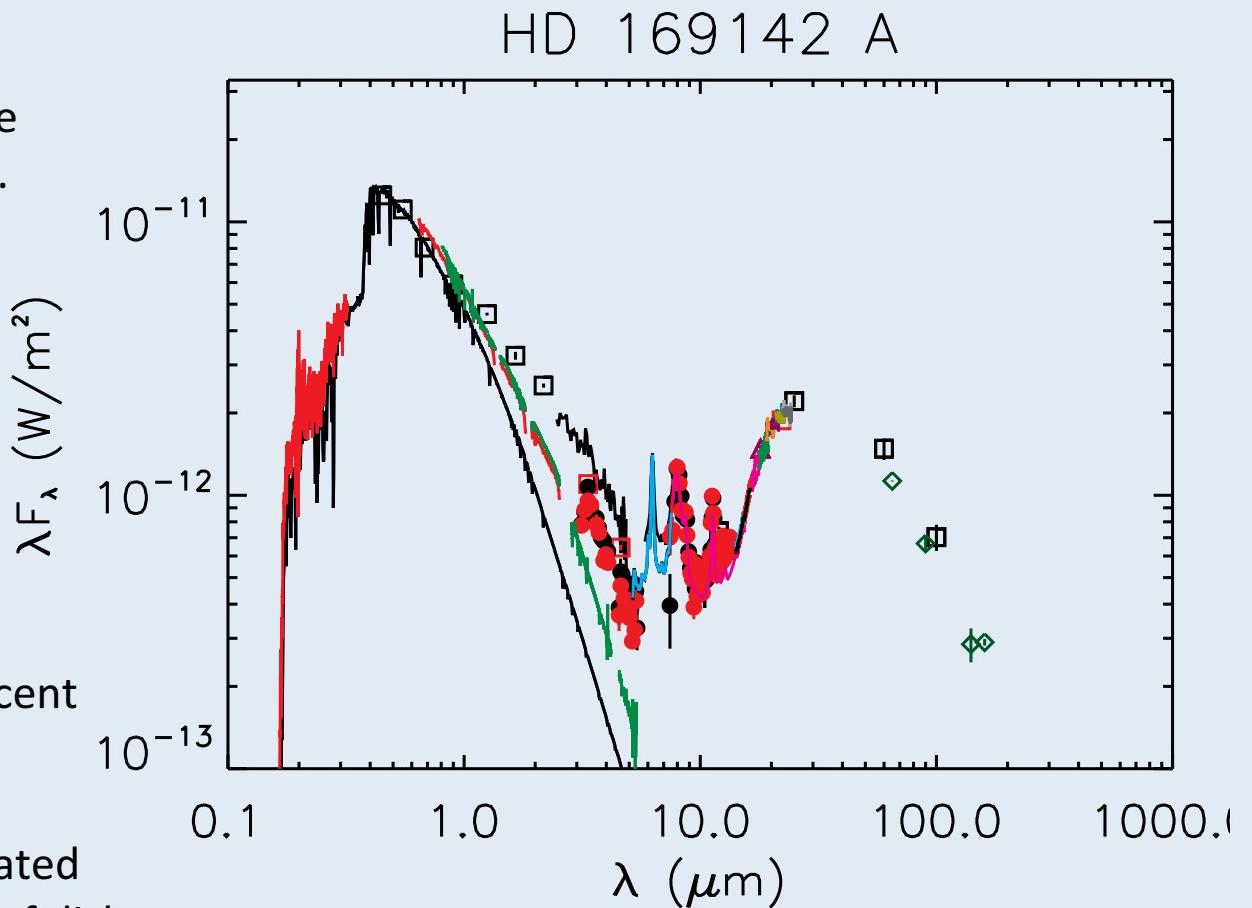
HD 169142

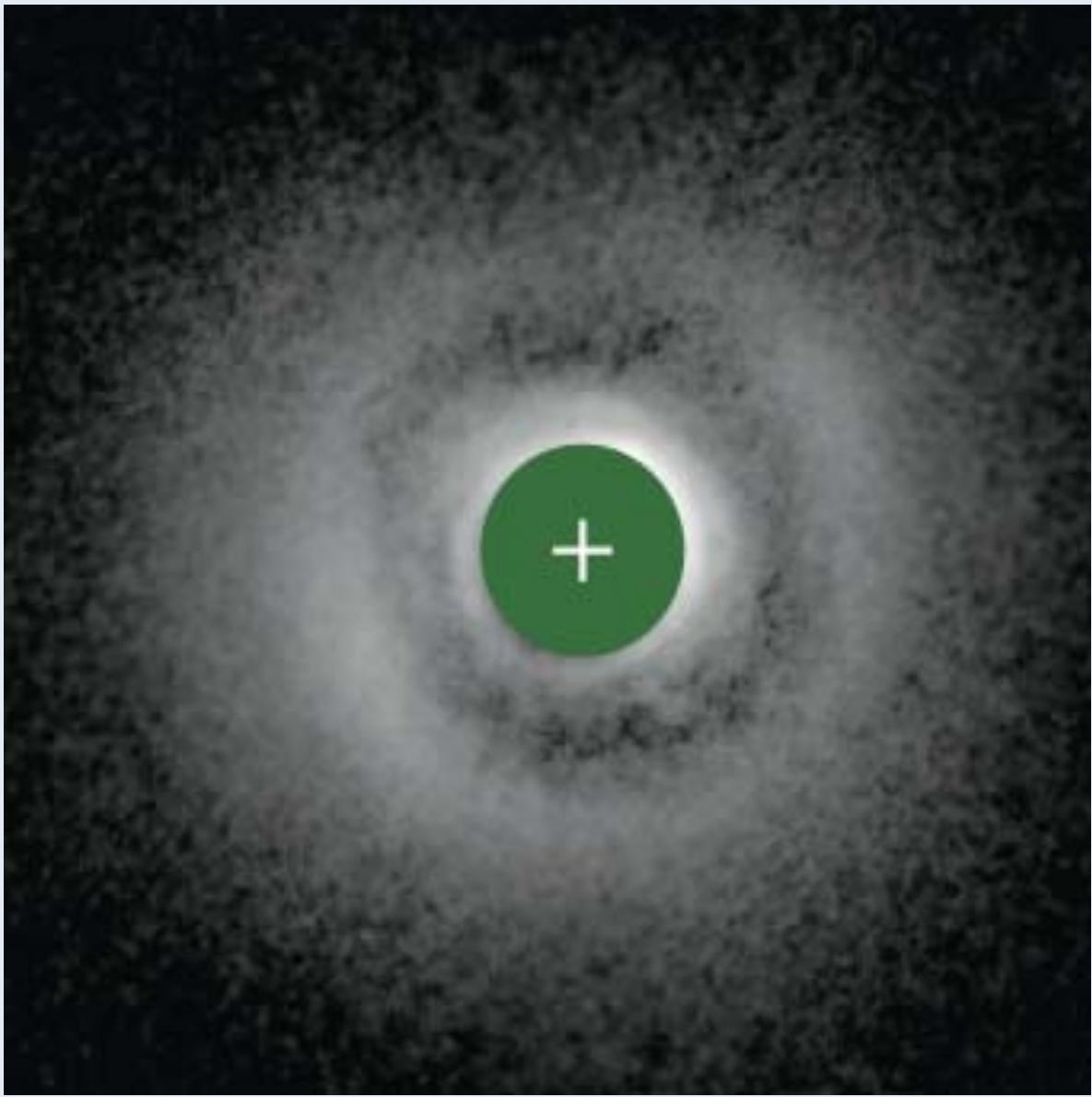
Identified as a non-variable SED in mid-IR (Kóspál et al. 2012)

Longer temporal baseline reveals SED variability

Recent data in low accretion state; high accretion state prior to 2000. Accretion rate for recent Data – $3.1 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$.

Low state may have facilitated Scattered light detections of disk.





HD 169142

HiCIAO H PI - Momose
et al. (in prep); similar to
Quanz et al. 2013

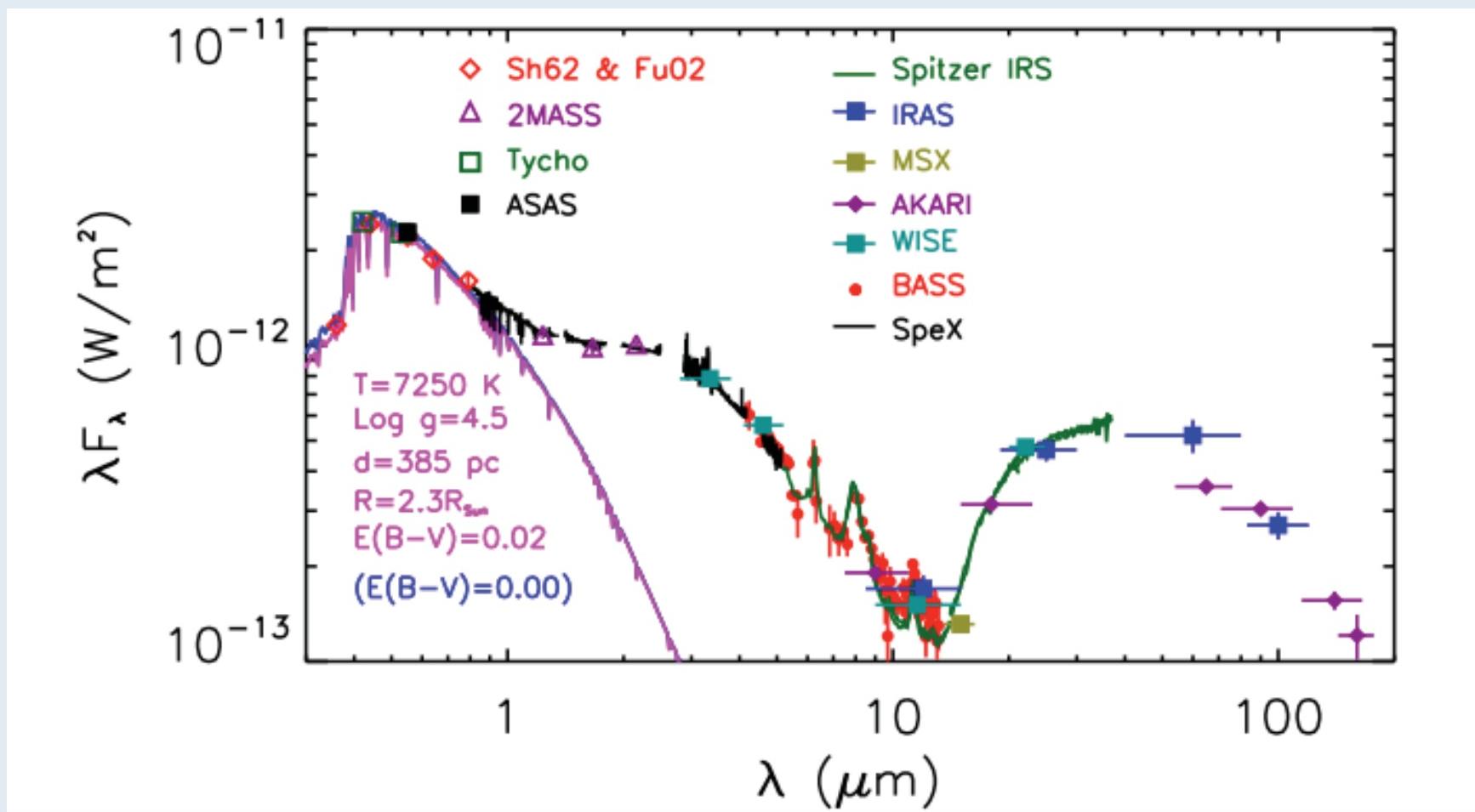
Asymmetric Shadows in Outer Disks

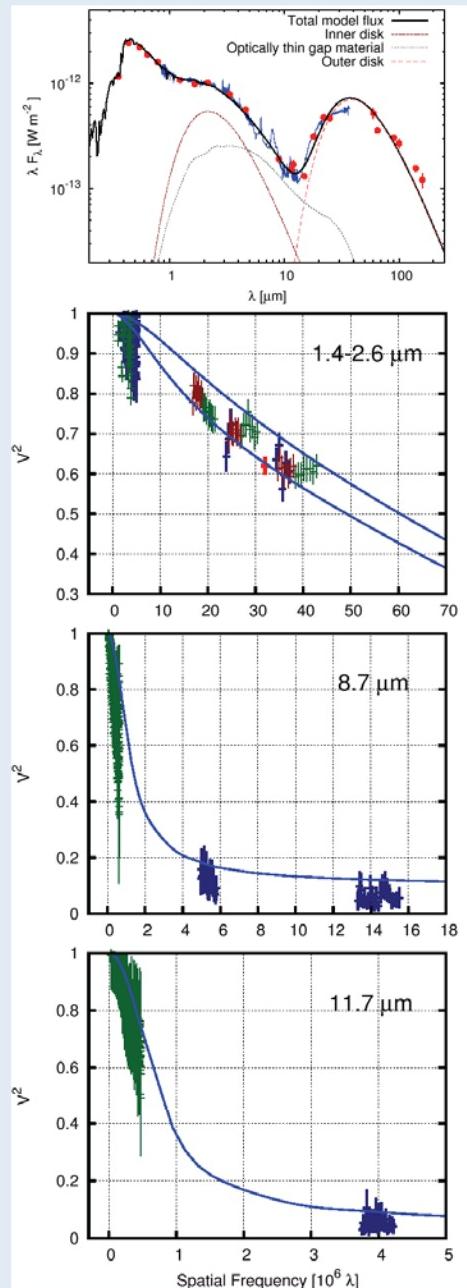
- SAO 206462 – bar-like structure in scattered light seen by HiCIAO, not so much by NACO - may indicate that there is variable shadowing of part or all of the outer disk. This may mean that the FIR is variable – available data too sparse to currently test (SPICA??)
- Duty cycles for outer disk shadowing not known, but may account for water detection in HD 163296 (Fedele et al. 2012).

Coordination with Interferometry

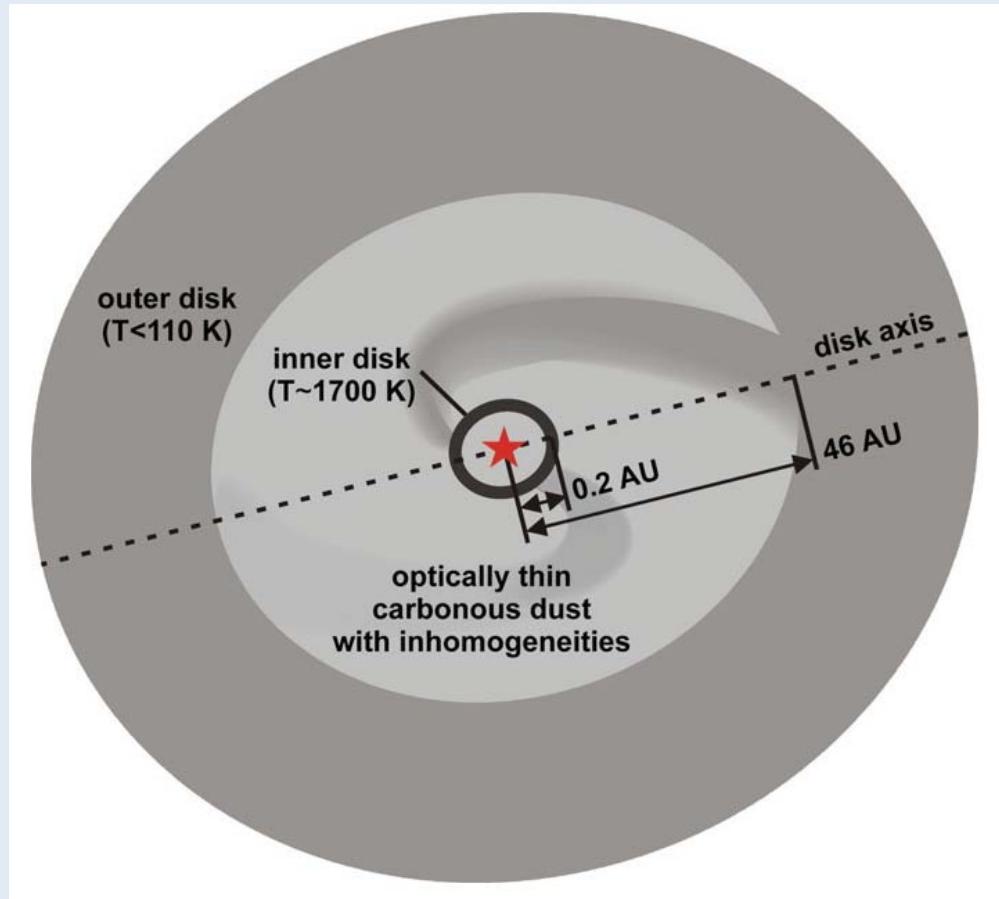
- Combining SED measurements with interferometry and sparse aperture masking can reveal gap structure and material within a gapped region (Kraus et al. 2013).
- Useful probe of disks which are located too far away for conventional high contrast imagery.
- SED data used to augment visibility data, particularly for inner disk.

V1247 Ori

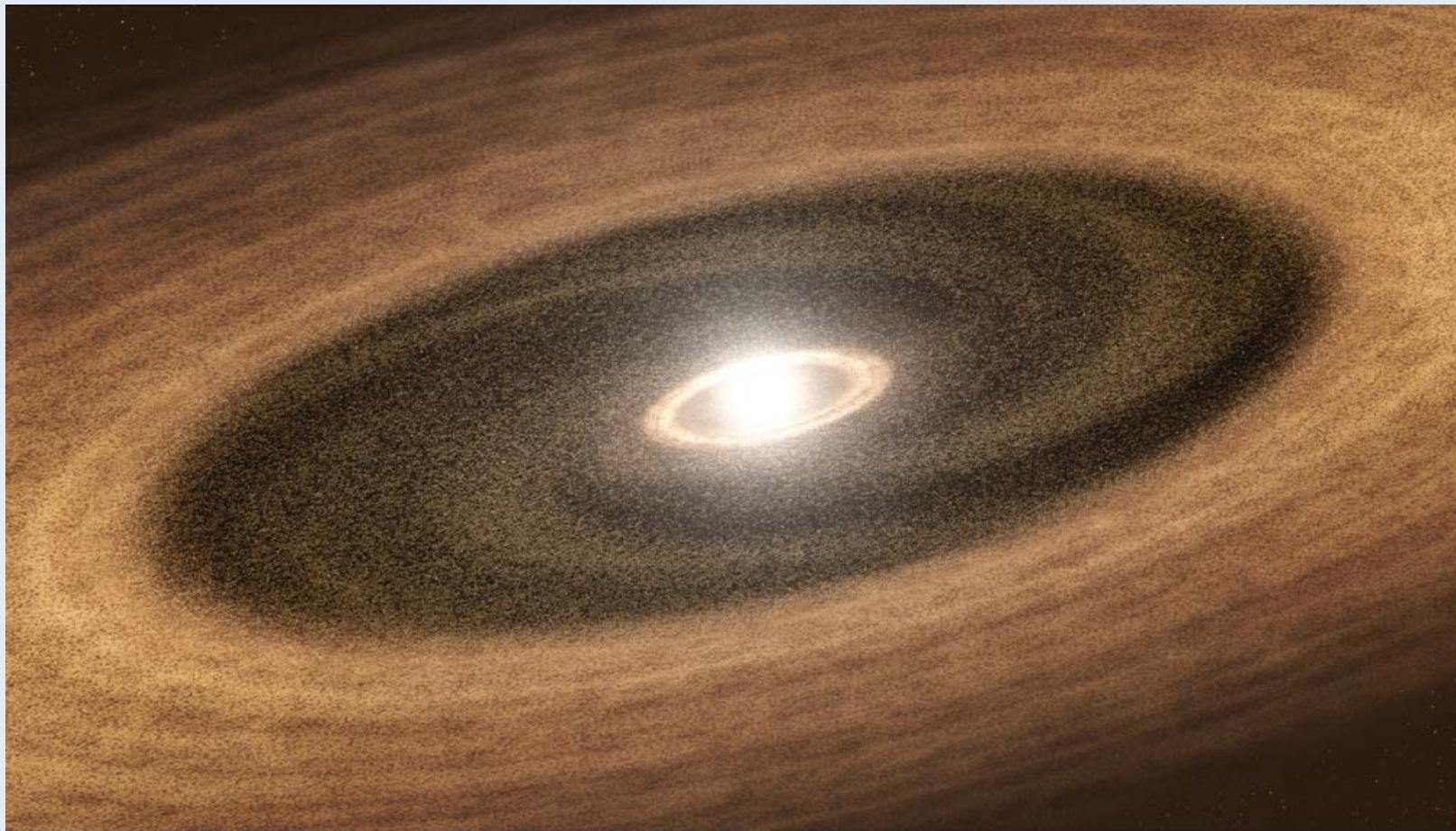




What do you get from this sort of thing? Confidence in using multiple techniques to constrain physical models.



Coordinated 1-13 micron SED information, combined with interferometry at multiple wavelengths constrained the structure of the inner disk of V1247 Ori. From Kraus et al. 2013.



Artist's rendition of V1247 Ori. NASA/JPL PlanetQuest web site

Conclusions

- Inner disk structure greatly affects visibility of outer disk in scattered light, and potentially also in thermal imaging.
- The available data suggest that the inner portions of both protoplanetary and pre-transitional disks are variable, host optically thick structures (they cast shadows).
- Understanding what you are seeing in high-contrast imagery, interferometry, including SAM observations, and mid-IR spectra requires knowledge of the SED best obtained with contemporaneous photometric or spectrophotometric data.